Composition and accumulation of recent sediments in Lake Michigan

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Introduction

Lake Michigan developed primarily by ice flow channeling during glacial retreats between 11.8 and 15.5 thousand years ago. With the final retreat of the glaciers and subsequent lowering of water levels, the lake passed through several configurations, finally reaching its current form 4-5,000 years ago (Colman et al., 1994; Larson and Schaetzl, 2001). The basin continues a slow rise from the isostatic rebound after the removal of glacial ice. Lake Michigan presently has a surface area of 57,800 km^2 and volume of 4,920 km^3, making it the third largest of the North American Laurentian Great Lakes and the sixth-largest lake in the world (Herdendorf, 1990). The lake is surrounded by a relatively small drainage basin of only twice its surface area (EPA, 1995). It couples with Lake Huron at the Straits of Mackinac in the north, and water exchanges occur in both directions (Saylor and Sloss, 1976). Net outflow to Lake Huron, plus small diversions into the Chicago River are the sole outlets, and only a tiny fraction (~1%) of the water volume is lost annually by combined outflow.

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The open lake has three principal bathymetric features: southern and northern basins plus a comparatively shallow mid-lake sill (<100 m) that separates them (figure 1). The southern basin is nearly symmetrical with shelves sloping downward into the 160 m deep central region. The southern basin has the largest river input, as well as the greatest density of municipal and industrial activities in the lake system. The northern basin is the deepest (maximum sounding – 281 m), and the northeastern region has a very complex topography of small ridges, valleys, and islands. The mid-lake high is a relatively shallow sill (<100 m) that extends outward from the western side of the lake. In addition to the open lake, there are large embayments in the northwestern and northeastern region, Green Bay and Grand Traverse Bay, respectively. Green Bay is relatively shallow with the largest single river input (Fox River) to the lake at its southern end. Grand Traverse Bay is split into two deep arms (160-180 m) giving the bay a fjord-like character.

Sources of particulate matter

Shoreline erosion is the major contributor of sediments to Lake Michigan (Rae et al., 1981) as it is for the other Great Lakes except for Ontario. For Lake Michigan, the erodable bluffs are predominantly along the southern and western shore of the lake. Although table 1 shows that more sand enters the lake than fine-grained materials, our focus in this chapter is on the fine-grained materials that are subsequently distributed throughout the lake. The sand primarily remains in the coastal regions of the lake. Since bluff materials constitute the vast majority of particle input (table 1) and there were no reported compositional information, we sampled a suite of 10 bluff locations from Indiana Dunes to the Door Peninsular of Green Bay. The composition of the bluffs ranged from coarse sand to a sandy-loam, with a <250μm fraction ranging from 12-68% of the mass. This fine fraction had an organic carbon content of 10.8 ± 6.9 mg C g^{-1} and 8.8 ± 5.5 mg C g^{-1} of inorganic carbon. The organic C/N (atomic) was 26 ± 4.

Tributaries are the second major source of particulate materials to the lake. Many of the lake tributaries drain both agricultural and municipal basins and

Table 1. Inputs of particulate matters to Lake Michigan in 10^6 t yr^{-1}

Reference		Erosion	River	Atmosphere	Total In	Total Out
Rae, 1981	Total	14.7	0.7	0.8	16.2	16.2
* Coleman, 1994	Mud	1.2	0.31	0.34	1.8	3.0
* Coleman, 1994	Sand	3.8	0	0	3.8	0

* (Colman and Foster, 1994) only used data from the southern half of Lake Michigan

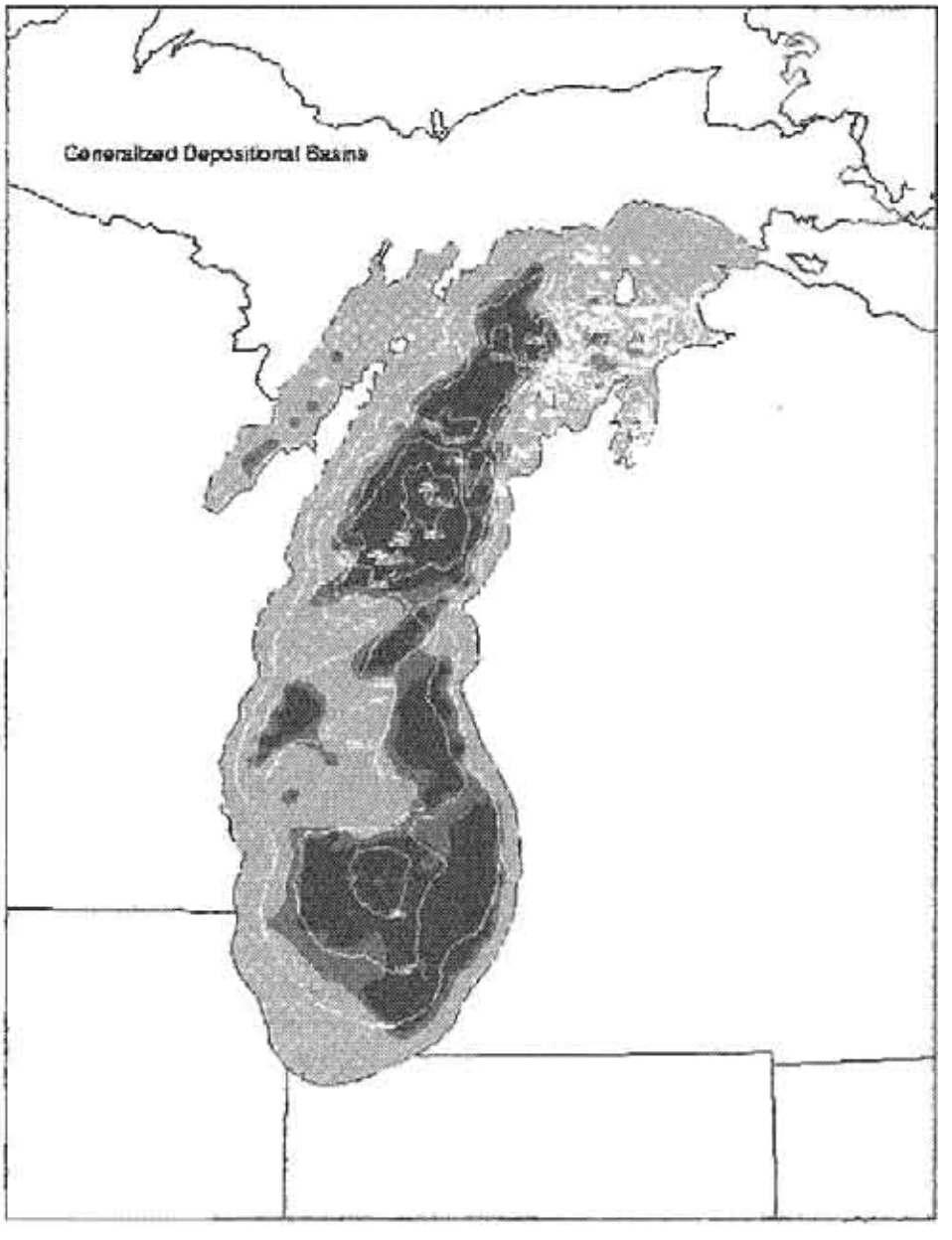

Fig. 1. Map of the generalized sediment depositional basins (from Cahill, 1981). Darkest areas represent regions of modern sediment accumulation; lightest regions are areas where modern sediments do not accumulate. Water depth intervals are shown for 50, 100, and 200 m.

introduce a significant fraction of anthropogenic compounds. The Grand and St Joseph Rivers, the two major tributaries to the open lake, are located on the eastern side of the southern basin. The Fox River, discharging into southern Green Bay, is the largest tributary but its load of solids is mainly deposited in the bay itself with little reaching the open lake. Only minor rivers are tributary to the northern basin and Grand Traverse Bay; thus they are not a significant source of solids to the open lake. Estimates of particle load from tributaries are summarized in table 1. Aeolian sources of particulate matter are similar in magnitude to the tributaries. These materials include dust and combustion by-products and are generally finer than tributary materials.

In addition, there are several types of particulate material that are produced within the lake. The dominant primary producers are the diatoms. These organisms produce an exoskeleton of amorphous silica in addition to converting dissolved inorganic constituents to particulate organic matter at a rate of approximately 12 mg C cm^{-2} y^{-1}, using reported spring-summer values of primary production (Fahnenstiel and Scavia, 1987) and half those rates for the other six months. Almost all of the biogenic silica remineralizes back to the dissolved form (Parker et al., 1977) and only about 5% of the organic matter reaches the sediments (Eadie et al., 1984) where it undergoes further decomposition. There are also three sources of calcium carbonate. A form of calcite precipitates annually from warm surface waters, especially in the southern part of the lake. Ancient carbonates, believed to be predominantly dolomite, erode from the Niagaran reef formations along the southern and western shore and shallows of the lake. Recently, the zebra mussels are producing a third source of carbonates. Much of the calcite dissolves when the lake cools, but carbonate concentrations can reach concentrations of over 25% in the sediments of the southeastern region of the lake.

Rae et al. (1981) estimated loadings to the entire lake using data from several sources (table 1). Subsequently Colman and Foster (1994) estimated loadings separately of mud (fine particles) and sand for the southern basin only using some of the same data along with a large amount of new information collected in a southern Lake Michigan shoreline erosion project (Folger et al., 1994). Since most shoreline erosion is in the southern half of the lake, the estimate for the whole lake used by Rae et al., derived from (Monteith and Songozni, 1976), appears to be too high. In the earlier budget, the output term (table 1) was set equal to the total input to balance the budget. In the more recent study the output term was independently estimated from sediment accumulation rates (Edgington and Robbins, 1976a).

Particulate matter in the water column

There are strong seasonal and vertical patterns of suspended material in the water

column. In the open lake, the near surface suspended matter ranges from 0.5 to 2 mg l^{-1} (figure 2) and is dominated by sediments resuspended in the late fall and winter, followed by diatoms in spring and early summer and finally an authigenic calcite precipitation beginning in late summer into early fall (Eadie et al., 1984; Robbins and Eadie, 1991). In the water column, the particle size distribution throughout the year is predominantly between 4 and 32 μm (Eadie et al., 1990). The late summer carbonate "whiting" event is common to all of the lakes except Superior (Strong and Eadie, 1978), and the size range of the authigenically precipitating $CaCO_3$ in Lake Michigan is 2-16 μm, with an average of 7 μm (Vanderploeg et al., 1987).

Particle settling and resuspension processes have been examined in Lake Michigan through the use of sediment traps since the mid 1970s (Eadie et al., 1984; Wahlgren et al., 1980). Cylindrical traps, designed for conditions in the Great Lakes (Bloesch and Burns, 1980; Muzzi and Eadie, 2002) are moored at selected depths to intercept materials settling to the bottom. Traps provide an efficient tool for the collection of integrated samples of settling materials for detailed analysis. Measuring the mass collected allows calculation of the gross downward flux of particulate matter and associated constituents. A mean particle settling rate is calculated as the ratio of mass flux to ambient suspended solids concentrations defined as the mean of values obtained at start and end of deployment. A long-term record from a 100 m deep site, 25 km off Grand Haven, MI illustrates these values (figure 3).

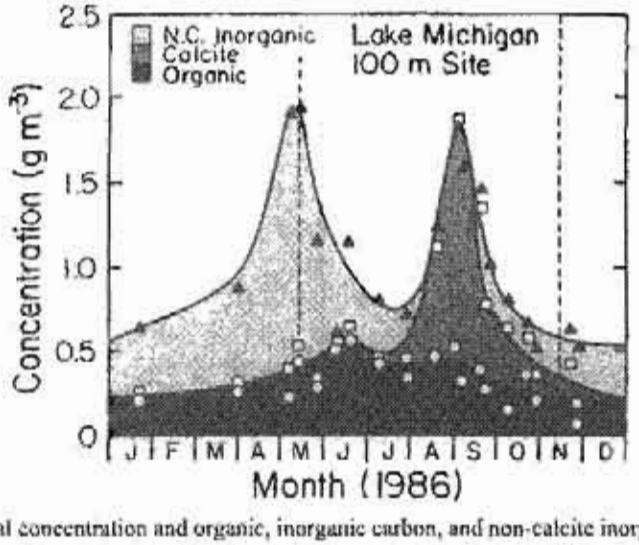

Fig. 2. Seasonal concentration and organic, inorganic carbon, and non-calcite inorganic suspended matter in near-surface waters at a 100 m deep site in southeastern Lake Michigan in 1986. The spring peak is primarily due to sediment resuspension prior to thermal stratification, while the late summer peak is due to $CaCO_3$ precipitation.

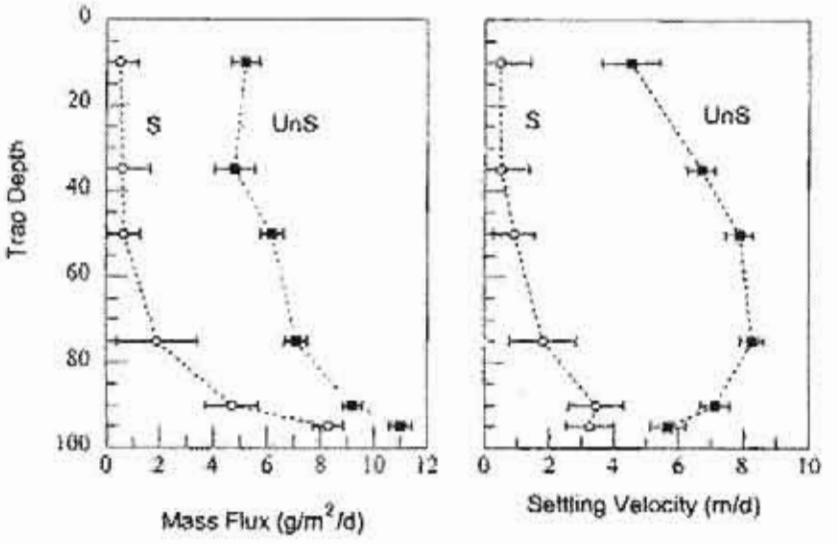

Fig. 3. A 24-year synthesis of profiles of trap measured mass fluxes and settling velocities. Error bars represent the coefficient of variation; the number of replicates ranged from 27 to 126. The stratified and unstratified periods are designated with an S and US respectively.

Profiles of sediment traps were first deployed at the 100 m deep site in 1978 and, for most years, sampling has continued since then. The long-term average mass fluxes measured from 1978 to 2002 are presented in figure 3. Throughout 2002, profiles of mass flux exhibit an exponential increase toward the bottom, a benthic nepheloid layer (BNL) beginning within 10-20 m of the bottom (Chambers and Eadie, 1981; Eadie et al., 1984). In the BNL, concentrations of suspended matter more than doubles, and mass fluxes show increases of up to a factor of ten. There has been some speculation on the formation and dynamics of the BNL (Chambers and Eadie, 1981; Eadie et al., 1984; Eadie and Robbins, 1987; Hawley and Murthy, 1995) but more definitive work is needed to determine its properties and overall importance in sediment transport. From late December through early June, Lake Michigan is virtually isothermal and well mixed. Average fluxes during this period are high throughout the water column. During the stratified period (June-December), the upper half of the water column becomes isolated from the large inventory of materials in the sediments, although episodic mixing does occur during upwellings. During this period, a strong BNL is clearly evident from the mass flux profile.

Average particle settling velocities also show substantial differences between the two thermal periods (figure 3). During the stratified period, these calculated settling velocities in the epilimnion (0.5-1 m d^{-1}) agree with those required to model the long-term behavior of fallout radiotracers (Robbins and Eadie, 1991). Settling

velocities estimated for the BNL (several m d^{-1}) shows clearly that frequent recharging of the BNL is required in order to maintain its observed persistence. The BNL is a regular feature in all of the Great Lakes and appears to be composed primarily of resuspended sediments. In the shallow waters of the shelf and slope, surface and internal waves and occasional strong currents resuspend sediments, sorting the particles and transporting them horizontally as well as vertically. The cycle of resuspension and redeposition has the effect of producing a resuspended pool composition that is relatively uniform within major basins of the lakes.

Long-term patterns of sediment accumulation

The first substantive efforts to examine the geology of Lake Michigan were conducted by Hough (Hough, 1958). This was followed by seismic profiling of sediments to characterize their stratigraphy on geologic time scales by Lineback et al. (Lineback et al., 1970; Lineback et al., 1971). They discerned an upper, most recent stratigraphic unit, the Waukegan Member (age ~ 3,500 y) of the Lake Michigan Formation, that was characterized by a gray silt in the center and eastern side of the southern basin (thickness up to 9.2 m) and a brown silt (thickness less than 0.3 m) along the western half of the southern basin and the mid-lake high (Cahill and Shimp, 1984). Surface sediment electrode potentials (Eh) were found to be lower in the gray silt (Cahill, 1981), consequently they are more reducing than the brown silt materials. It was speculated (Cahill and Shimp, 1984) that the more reducing conditions was caused by microbial decomposition of the organic matter coming from the rivers on the southeastern portion of the lake. However, this unit was not uniformly resolved across the lake floor, especially in areas over the mid lake silt and on the western side of the lake where modern sediment accumulation rates are known to be low.

A subsequent study (Colman et al., 1994) was unable to discern a unique Waukegan Member over the entire southern basin, and restricted their interpretation to an upper (single unit) and lower (seven units) designation for the Lake Michigan Formation. The upper unit contained the gray to brown silts and is separated from the lower Lake Michigan Formation by the Chippewa unconformity, a transgressive period lasting from 10.3 to 4.8 ka. The sediment accumulation illustrated in figure 4 (Foster and Colman, 1990) represents the materials accumulated since the Chippewa unconformity, approximately 10 ka. The dates are based on ^{14}C analyses of carbonates and are uncorrected for the presence of old carbon in the system (hard water effect) estimated to make the dates too old by approximately 500 years (Colman et al., 1994).

The Upper Lake Michigan Formation of postglacial sediments is asymmetric (Cahill, 1981; Foster and Colman, 1990; Lineback and Gross, 1972), with the

greatest accumulations found in a series of basins about 20 km from the eastern shore and decreasing towards the deepest sounding in this basin (figure 4). These accumulation basins, with sediment thickness up to 20 m, are on the slope, and sediment thickness decreases towards the deep, central portions of the lake. There is essentially no accumulation of sediment on the southwestern portion of the basin, and little along the western side of the lake. There is also a large region in the central part of the lake where sediment has not accumulated.

Recent patterns of sediment accumulation

Modern approaches to the measurement of sediment accumulation rates in Lake Michigan were first applied on a suite of carefully collected gravity cores (Robbins and Edgington, 1975). They used profiles of two radionuclides: ^{137}Cs, an anthropogenic isotope ($t_{1/2}$=30 y), with a well measured source to the Great Lakes (Robbins, 1985), produced in the atmospheric detonation of thermonuclear devices; and ^{210}Pb, ($t_{1/2}$=22.3 y), a natural decay product of ^{238}U. They also developed models necessary to convert the measurements into geochronologies. Refined models, along with their assumptions and limitations have been further developed over the years (Edgington and Robbins, 1976a; Robbins and Herche, 1993). The two radionuclides can provide complementary information, since the rate of delivery of ^{210}Pb is approximately constant, while the delivery of the ^{137}Cs arrived as a pulse, mostly between 1960 and 1963. Both have a high affinity for particles, although ^{137}Cs is preferentially associated with clays while the ^{210}Pb is less selective, although it does appear to co-precipitate with calcite during the annual lake wide "whitings" (Van Hoof and Andren, 1989). When compared to the steady-state profiles of ^{210}Pb, the pulsed ^{137}Cs data can provide information relating to in-lake processes occurring from multi-year to multi-decade time scales.

Radiometric analysis of eight cores (Robbins and Edgington, 1975) yielded a range of linear sediment accumulation rates from 0.07 to 0.28 cm y^{-1} and surface mixing depths (bioturbation) of 0-4 cm. The accumulation rates were shown to correlate well with the thickness of the Waukegan Member. Subsequent analysis of 13 cores from the southern basin (Edgington and Robbins, 1976a) provided an estimate of the mean net mass accumulation rate for the basin of 7.0 mg cm^{-2} y^{-1} using both stable Pb and ^{210}Pb. Depth-integrated inventories of ^{137}Cs from 51 cores in the southern basin (Edgington and Robbins, 1976b) produced an accumulation map very similar to the high depositional region in southeastern Lake Michigan identified in the Waukegan Member as well as the upper Lake Michigan Formation (figure 4). Discontinuities in the ^{210}Pb profiles in two cores from the high depositional region in the southeastern basin were correlated with major storms over the past century. This is the first record of storm-induced sediment transport

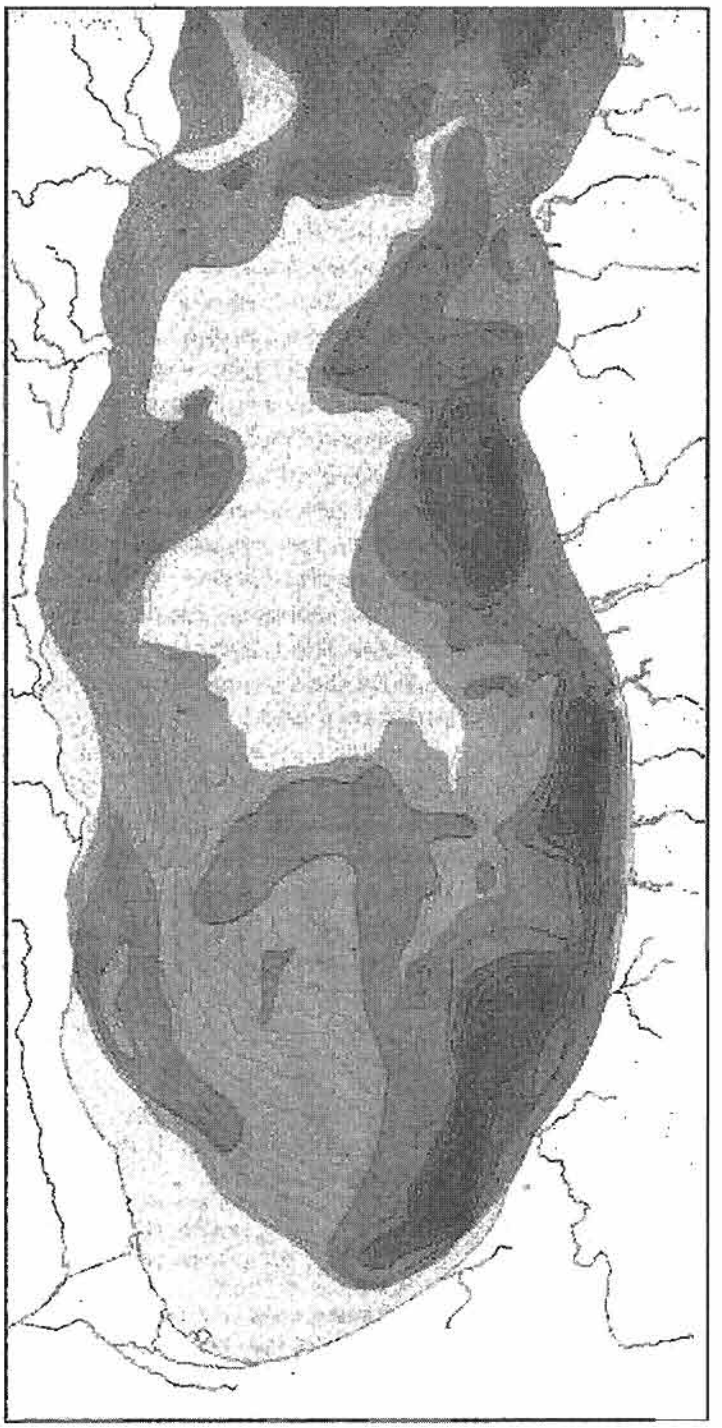

Fig. 4. Sediment accumulation patterns in southern Lake Michigan as measured by the thickness of post-glacial sediment (Foster and Colman, 1990). This Upper Lake Michigan Formation (~10,000 y) was found throughout the region mapped. The white region represents zero accumulation, and the lightest gray represents accumulation of 0-2 m; the remainder of the contours is in 2 m intervals with the darkest region having 20 m of accumulation.

in the Great Lakes, an interpretation that has grown in importance over the years (Eadie et al., 2002; Eadie et al., 1996; Hermanson and Christensen, 1991; Mortimer, 1988). A synthesis of all mass accumulation data results in a lake-wide average of 23 mg cm^{-2} y^{-1}.

Within a decade of its production (Edgington and Robbins, 1976c; Edgington and Robbins, 1976b) ^{137}Cs and (co-produced) $^{239+240}Pu$ had moved into the depositional region in the southeastern basin producing patterns similar to long-term accumulation. The detailed coring grid in the southeastern depositional region, collected in 1972, was revisited in 1982 to test whether "focusing" of sediments tagged with ^{137}Cs was completed by 1972 or had continued during the subsequent decade (Edgington and Robbins, 1990). Resulting contour plots of the two sets of ^{137}Cs inventories clearly showed that there was a net movement from the edges of the basin, or from outside the basin, into the regions of highest deposition. Thus, while the majority of sediment "focusing" had occurred within the first decade after introduction of the majority of the tracer, the process continued. Sediment trap data, discussed below, has provided further confirmation of sediment remobilization, primarily by storms during the unstratified period. Inventories of radionuclides, or any other constituent with a known source and post-depositional alteration, can be used to estimate a focusing factor. This is defined as the ratio of the total inventory of constituent in the core to the total amount delivered to the lake and averaged over the lake area. The definition must be modified if the lake is not closed (no significant outflow) with respect to a specific constituent. Both ^{137}Cs (Hermanson et al., 1991; Robbins, 1985) and unsupported ^{210}Pb (Golden et al., 1993) have been used to estimate lake wide loadings of other constituents from a few cores. This method of estimating mean loadings based on atmospherically delivered radionuclides is certainly not valid if there are significant

Table 2. Net Mass Accumulation Rate (mg cm^{-2} y^{-1})

Region	Range	N	Reference
Southern Lake MI	12 – 94	4	(Robbins and Edgington, 1975)
	2 – 93	16	(Edgington and Robbins, 1976a)
	40	1	(Golden et al., 1993)
	1 – 7.4	8	(Hermanson and Christensen, 1991)
Northern Lake MI	15 – 21	3	(Robbins and Edgington, 1975)
	8 – 11	3	(Edgington and Robbins, 1976a)
	28 – 36	2	(Golden et al., 1993)
	5 – 14	6	(Hermanson and Christensen, 1991)
Green Bay	23 – 189	5	(Hermanson and Christensen, 1991)
	2 – 155	63	(Manchester-Neesvig et al., 1996)
Grand Traverse Bay	100 – 110	2	(Cohen, 2001)

point sources of constituents. Any focusing factor calculation is approximate at best since it assumes that a constituent of interest behaves exactly the same as the focusing estimator. In fact, a recent, as yet unpublished, study has shown that, even for inventories of ^{137}Cs and co-produced ^{239}Pu that entered the lake in an essentially fixed ratio, there are systematic lake-wide differences of up to 30%.

Between 1987 and 1990, a comprehensive suite of 123 cores or grab samples were collected in Green Bay (Manchester-Neesvig et al., 1996) providing detailed map of net mass sedimentation rates (table 2) averaging twice (46 mg cm^{-2} y^{-1}) than the open lake. Sediment accumulation was mostly concentrated in the southern half of the bay where values exceed 70 mg cm^{-2} y^{-1} (Manchester-Neesvig et al., 1996). Maximum accumulation in the bay is approximately twice the highest rate found in the southeastern Lake Michigan depositional zone (table 2). Most of the material accumulating within the bay is derived from the Fox River and other smaller rivers in the southern region of the bay. The highest concentrations of organic carbon (~5%) were also concentrated along the southeastern region of the bay (Cahill, 1981).

Grand Traverse Bay is smaller in area, but substantially deeper than Green Bay. The southern portions of both arms are somewhat isolated from Lake Michigan by a relatively shallow sill. A suite of 67 sites were sampled with a Ponar^{tm} grab for surface sediments and analyzed for grain size, organic carbon, and trace metals (Baker-Blocker et al., 1975). The highest concentrations of organic carbon (5.3%) and trace elements were found in the depositional areas in the deeper regions of both arms of the bay. Two cores, collected in the western arm in 1998 for trace organic analysis, had similar accumulation rates of 100 mg cm^{-2} y^{-1} (table 2), higher than most sites in the lake.

Characteristics of recent sediments

In addition to the sampling programs described above, there have been three major whole-lake sediment sampling efforts. In 1975, the Canada Centre for Inland Waters and the Illinois Geological Survey collected 286 samples on a systematic grid and analyzed the upper 3 cm for 48 chemical elements, Eh, pH, and grain size (Cahill, 1981; Cahill and Shimp, 1984). Interpretation of these measurements led to classifying the surficial sediments as being from depositional or non-depositional areas, in general agreement with the acoustic survey data (Lineback et al., 1970; Lineback et al., 1971). Cluster and principle component analysis demonstrated that anthropogenic trace metals were correlated with the fine grain sediment fractions and organic carbon.

Using the Cahill data as a guide, the University of Wisconsin Sea Grant supported the collection of ca. 80 box and (a few) gravity cores from all depositional basins

of the lake in 1992. Finally in 1994-96 the EPA sponsored Lake Michigan Mass Balance and Environmental Monitoring and Prediction programs complemented the 1992 set with an additional 56 box cores from the depositional regions and 75 Ponar[sm] grab samples in non-depositional areas. Profiles of ^{137}Cs and ^{210}Pb were determined for the 134 box and gravity cores collected between 1992 and 1996 (Robbins et al., 2005). Vertical sediment transport models were used to interpret profiles, providing contour maps of open lake state variables such as net mass accumulation rates, rates and depths of near-surface sediment mixing, and residence times of particles in the mixed layer.

Grain size distribution

The 286 surface sediment samples collected in 1975 were analyzed for grain size distribution (Cahill, 1981) along with the 119 collected during the 1990s (Eadie and Lozano, 1999). Although the former were all collected by a Shipek grab sampler, and the upper 3 cm were composited, the size data were not different from the 0-1 cm box, gravity, and Ponar[sm] collections except for three locations where the newer box core data were used. The resultant data are shown in figure 5, where the distribution of fine grain (<60 μm) materials show patterns similar to those of the sediment accumulation map (figure 4). The depositional basins along the eastern side of the lake and in the deep northern basin are comprised of nearly 100% less than 60 μm materials. The mid-lake high and non-depositional regions in the west and south of the southern basin are low in the fine-grained materials (less than 40% of <60 μm over this area). The southeastern region of highest accumulation (figure 4) is visually linked to the deep central basin via a corridor of <60 μm materials.

During the 1994-96 sediment collection program, the protocol was to first collect a ponar grab sample and evaluate from that whether a box core collection would be feasible. In marginal situations, a gravity core was collected rather than deploying the more expensive box coring device. The resultant grain size distribution among the three types of sediments (figure 6) shows that the box cores, collected in depositional areas, were comprised mostly of materials less than 60 μm, with the majority of the mass between 8 and 60 μm. Gravity cores were intermediate. The Ponar samples, as expected, had much more material in the larger size fractions. Similarly, (Cahill, 1981) reported that samples from depositional regions had a smaller mean grain size than non-depositional sediments, and that the mean grain size in both categories decreased with depth. All sampling methods recovered similar mass fractions below 8 μm. It appears that significant amounts of fine materials can be occluded in sandy inshore deposits. These deposits can "sequester"

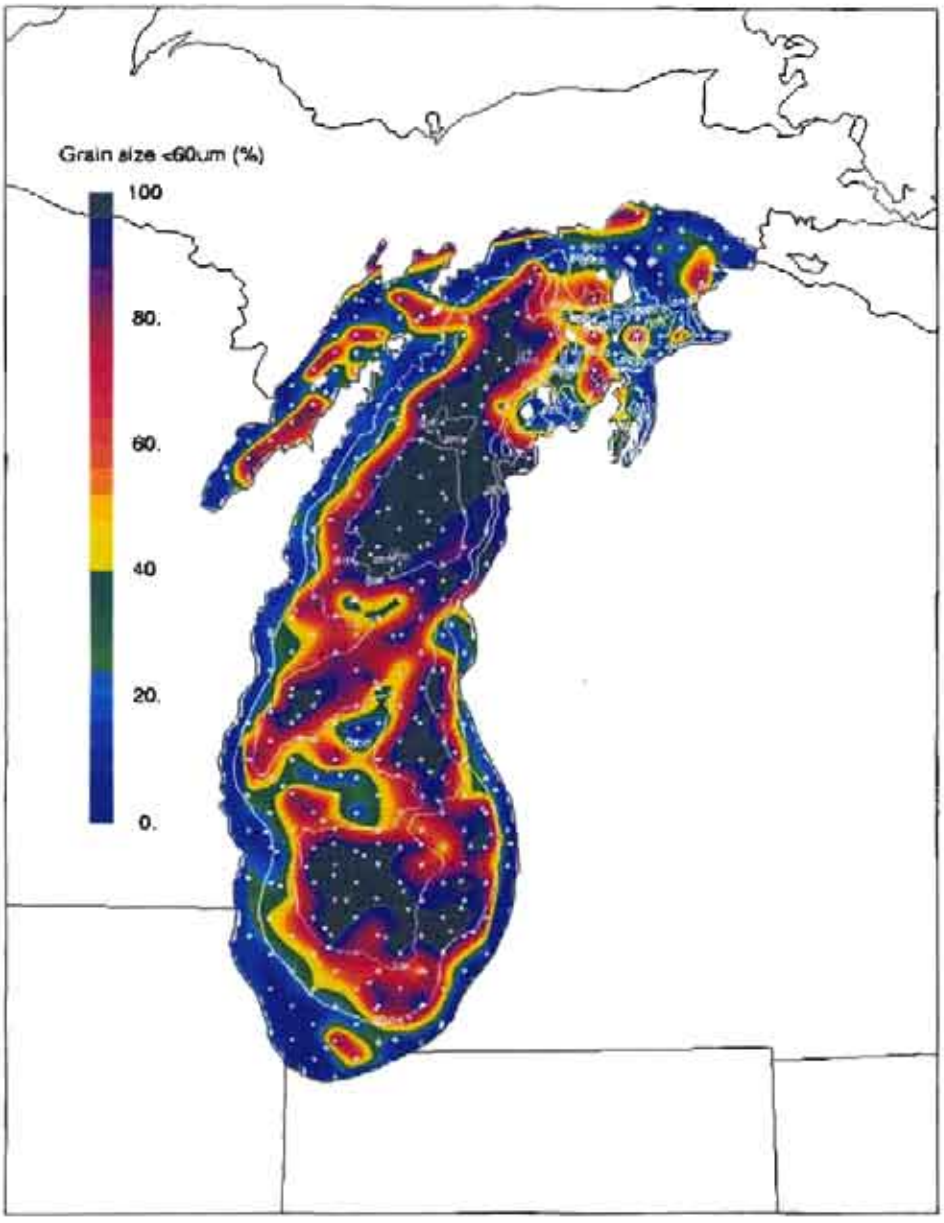

Fig. 5. The distribution of surface sediments with grain sizes of <60 im.

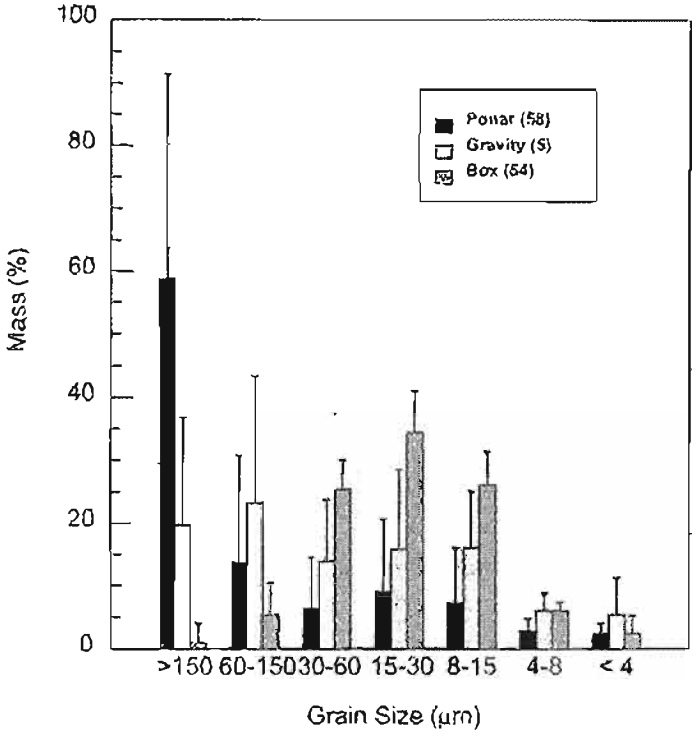

Fig. 6. Surface grain size distribution from samples collected from 1994 to 1996 throughout the lake. There were 54 box cores from depositional areas, 5 gravity cores from intermediate areas, and 58 ponar grab samples from non-depositional areas. Error bars represent 1 standard deviation.

contaminant laden fines that can, under sufficiently energetic near bottom current regimes, can be transferred back to overlying water.

Organic carbon and $CaCO_3$

The distribution of organic carbon from the 286 samples collected in 1975 showed high concentrations in the depositional basins (Cahill, 1981), with several samples in the southeastern depositional area exceeding 7.5% organic carbon. These values were substantially greater than surface (0-1 cm) concentrations of organic carbon (figure 7a) measured in the 1994-96 suite of cores, thus eliminating the possibility of combining the data sets. The higher values measured in the 1975 samples may be due to the presence of high concentrations of carbonates in the southern basin (figure 7b). We found that a portion of such carbonates were resistant to removal by standard acidification methods and speculate that these may be high Mg calcite or dolomite from the Silurian dolomite formation in the southern and western regions

of the lake and basin (Foster and Folger, 1994). An average of 12.6% dolomite was reported (Rossmann et al., 1986) in a grid of nearshore (<24 m depth) surface sediments in southeastern area of the lake. The highest concentrations of organic carbon in the 1994-95 sediments occur in the deeper portions of the lake and less associated with the regions of high sediment accumulation. Carbonates are concentrated in the southeastern portion of the lake and are associated with the depositional areas in the southern part of the lake. The carbonates are generally lower in concentration in the northern half of the lake and not as focused into depositional regions.

Sediments as a reservoir

Many contaminants entering Lake Michigan are rapidly removed (scavenged) from water because of their strong affinity for a variety of settling particles. Efficient scavenging ensures that, within a few years of introduction, more than 90% of the input has been delivered to sediments. Since the hydraulic residence time of the Lake is so long (100 yr) compared with characteristic times of residence in water (1-2 years), essentially the entire load of particle associated, non-degradable anthropogenic contaminants delivered during the past several centuries now reside at the bottom of the lake.

While sediments act as a vast reservoir of contaminants, small amounts continue to return to overlying water. Studies (Eadie et al., 1984; Robbins and Eadie, 1991), have shown that this is primarily the result of an annual cycle of sediment resuspension and redeposition releasing constituents from sediments back into the water. The long-term, virtually exponential post-fallout decline of ^{239}Pu and (decay-connected) ^{137}Cs in water has about a 20-year time constant (Wahlgren et al., 1980), which probably characterizes the net rate of incorporation of these tracers into permanent sediments (Robbins, 1982), a relatively long and inefficient process. The exponential character of the decline indicates that amounts returned to water originate from a sedimentary pool of resuspendable sediments in which contributions to it have been time averaged. This probably is a result of mixing of near-surface sediments by a combination of physical and biological processes.

When examining the distribution of concentrations in "surface" sediments, one must acknowledge that they are conceptually integrating through time. The "age" of the "surface" samples spans a range from 0 to 100 years in southern Lake Michigan (Edgington and Robbins, 1976c; Robbins and Edgington, 1975) and from 0 to 80 years in Green Bay (Manchester-Neesvig et al. 1996). This value can be estimated by dividing the thickness of the sampling interval by the estimate of sediment accumulation rate. Thus, our exercise of measuring concentrations of various constituents in the upper 1 cm of sediment slices through a spectrum of

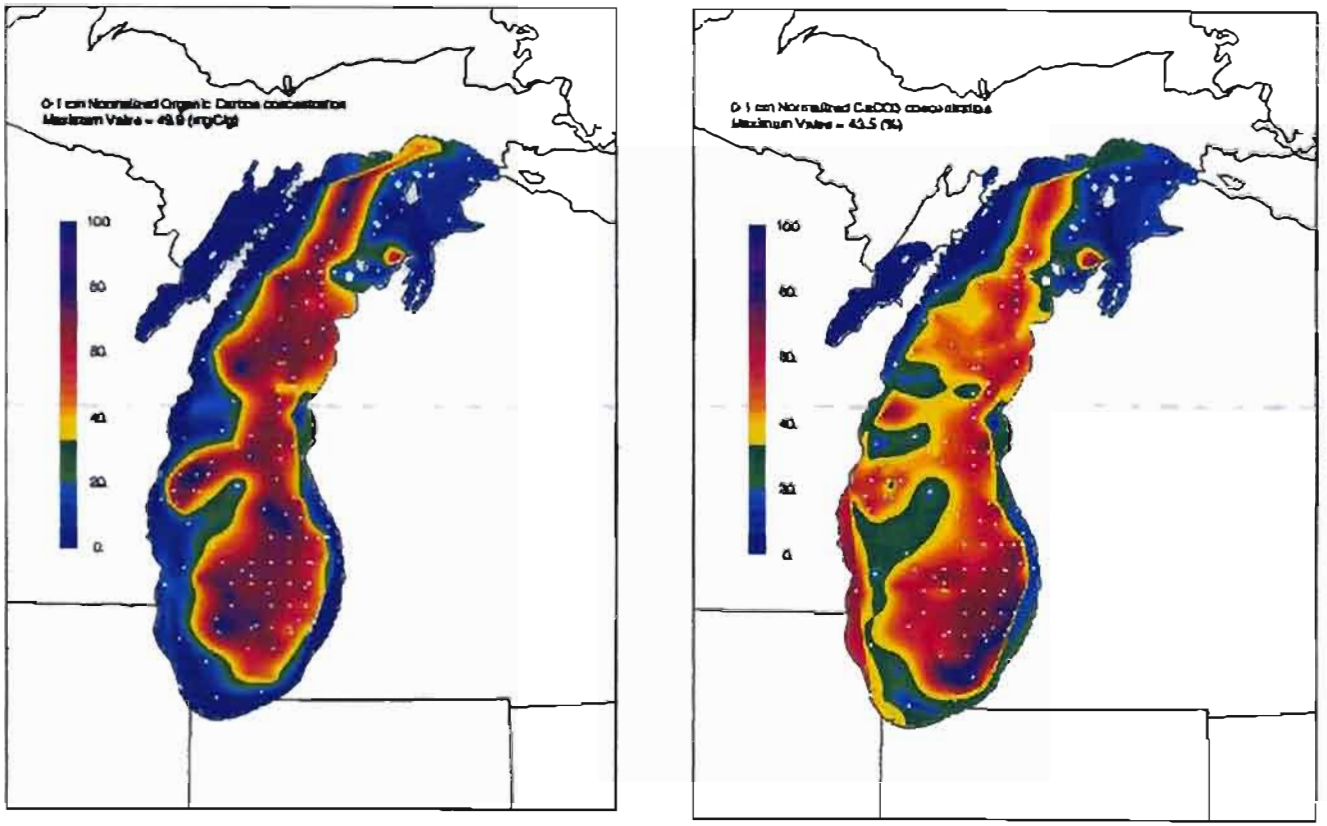

Fig. 7. a). The distribution of surface sediment organic carbon concentration from the 1994-96 samples. The maximum value was 49.9 mg OC g^{-1} (5%). b). The distribution of surface sediment inorganic carbon concentration, represented as $CaCO_3$, from the 1994-96 samples. The maximum value was 43.5%.

time, and the resultant patterns may include all or only a portion of a transient load (e.g. ^{137}Cs, PCB). Various locations have undergone different levels of diagenesis. During the years that these materials are part of the resuspendable pool, they constitute the major non-point source of nutrients and contaminants to the pelagic system. This material serves as a food source for surface deposit feeders and is consequently mixed during their feeding activities, a process termed bioturbation (Robbins, 1982; Robbins, 1986; Robbins et al., 1989). This pool also is probably the source for some of the material that makes up the benthic nepheloid layer (Chambers and Eadie, 1981; Eadie and Robbins, 1987) which plays a major role in coupling the inventory of constituents in surface sediments with overlying lake water throughout the year. The materials in these transient reservoirs are biogeochemically transformed within the lake, then redistributed throughout the year by a spectrum of energetic events.

Sediment particles (and their associated nutrients), radionuclides, and exotic organic compounds are predominantly transferred within the coastal zone of large lakes and enclosed seas in episodic pulses (storms, spring runoff). The resuspension of surface sediments in the Great Lakes, containing the large inventories of nutrients and contaminants deposited over the past few decades, presently results in greater fluxes to the water column than from external inputs (Brooks and Edgington, 1994; Eadie et al., 1984; Eadie and Robbins, 1987; Eadie et al., 1990; Robbins and Eadie, 1991). The trap profiles, along with satellite imagery (Eadie et al., 1996) and other evidence show that particle transport is concentrated in the unstratified period and appears to be episodic. The most energetic currents and waves occur during storms. One major event, which appears to occur annually in southern Lake Michigan, is the formation of a coastal turbidity plume in late winter-early spring. These events were first documented (Mortimer, 1988) from satellite images obtained during the late 1970s and early 1980s. For the past several years, intermittent satellite coverage has revealed the presence of the plume in the visible wavelengths with a clear offshore projection that coincides with the region of maximum sediment accumulation in the lake. In the southern basin of Lake Michigan, alongshore currents are initially driven by pulses of wind, but can subsequently reverse direction as the characteristic two gyre wind-driven circulation pattern rotates around the basin as a two cell vorticity wave (Beletsky and Schwab, 2001; Beletsky et al., 1999; Saylor et al., 1980; Schwab, 1983). The relaxation time of this response is in the order of several days. Because the predominant winds are from the west, circulation in the southernmost part of the southern basin is more frequently counterclockwise (cyclonic) than clockwise. Because of the orientation of Lake Michigan, northerly winds generate the largest waves (in the southern basin), and, therefore, the greatest energy available for resuspension of nearshore sedimentary material, and would also contribute to southward transport very near the shore in the southwestern part of the lake (Lou et al., 2000).

Contaminant patterns

A population of over 10 million residing within the basin coupled with its long hydraulic residence time has resulted in critical issues relating to anthropogenic contaminants. Analysis of the composition of the 1975 sediment samples (Cahill, 1981; Cahill and Shimp, 1984) concluded that the depositional and non-depositional areas could be delineated from grain size information. Trace elements, such as Br, Cr, Cu, Pb, and Zn were highly enriched in surface sediments of depositional regions. Organochlorine compounds in these same surface sediments, analyzed with a packed column GC, also were highest in depositional regions (Frank et al., 1981), although differences in the concentration patterns in sediments implied specific sources, such as the Fox River, and the Milwaukee and Waukegan Harbors for PCBs.

PCB manufacture and use were banned in 1977, but interest in this suite of compounds has continued, since they may cause chronic harm as endocrine disrupters. They serve as an example of the pathways of hydrophobic organic materials in the lake. Sediment samples collected from 1978 to 1980 in the southern basin, and analyzed using a high-resolution capillary GC, showed patterns similar to the 1975 data (Frank et al., 1981). Average PCB concentration in the depositional regions was 81 ng g^{-1} and only 7.2 ng g^{-1} in the non-depositional regions examined. The survey also found very high concentrations of PCB in the Waukegan Harbor (up to 3,600,000 ng g^{-1}). In two sets of dated cores, estimates of PCB flux to the sediments of Lake Michigan range from 6.9 to 10 μg m^{-2} y^{-1} (Hermanson et al., 1991; Strachan and Eisenreich, 1988; Swackhamer and Armstrong, 1988). PCB inventories, corrected for focusing, ranged from 24 to 144, with an average of 67 ng cm^{-2} (Hermanson et al., 1991) and 80-205, with an average of 125 ng cm^{-2} (Golden et al., 1993) in the open lake.

The concentration of PCBs in Green Bay is higher than the open lake due to the large inputs from the Fox River. Concentrations near the river mouth have been measured at 2,730 (Swackhamer and Armstrong, 1988) and 2,000 ng g^{-1} (Hermanson et al., 1991). Congener distribution in the bay is different from the open lake with higher concentrations of lower chlorinated materials present in the bay. A long history of PCB use in the paper industry along the Fox River and these high PCB concentrations led to a major EPA study in the late 1980s. A major sediment survey (169 sites) was undertaken to map PCBs and sediment accumulation in the bay (Manchester-Neesvig et al., 1996). Both maximum sediment accumulation rates and maximum PCB concentrations were confined to the southern portion of the bay. It was estimated that the bay contains 8,500 Kg of total PCB.

Mercury concentrations in recent sediments have been reported several times (Cahill, 1981; Kennedy et al., 1971) and have recently been summarized (Rossmann,

2002). Concentration patterns for the three studies are generally similar, appear to be declining, and generally conform to bathymetry, with some elevation in the southeastern depositional region. Concentrations in the 118 locations collected from 1994-96 ranged from 2-260 ng g^{-1} and averaged 78 ng g^{-1}. The estimated flux into the depositional basins was 7.2 ng cm^{-2} y^{-1}. Higher concentrations and fluxes were found in Green Bay (Rossmann and Edgington, 2000), with concentrations up to 1100 ng g^{-1} and the average flux to the sediment was 20 ng g^{-1}.

The lake sediments thus represent a major transient reservoir for the particle-associated materials delivered to the lake. In-lake mixing processes and local bioturbation combine to create a reservoir representing decades of inputs available for exchange through resuspension and biological pathways. Large episodic events resuspend, sort, and transport these materials from temporary sinks to more permanent sinks with a small fraction becoming incorporated annually into the sediments of the depositional basins. The lake average time constant for this removal is estimated to be 20 years. During these resuspension events, there is an opportunity for the lake to re-equilibrate with the constituents in the resuspendable pool of the sediments representing years to decades of constituent loading.

Summary

Lake Michigan sediments are a dynamic reservoir of materials. In-lake mixing processes and local bioturbation combine to create a reservoir representing decades of inputs available for exchange through resuspension and biological pathways. Bluff erosion is the main external source (ca. 66%) of new particulate material to Lake Michigan with tributary and aeolian particulate matter contributing about 12% each. These materials acquire signatures characteristic of the lake and migrate toward depositional basins, primarily along the eastern slope of the lake. The majority of this transport occurs within a few years, although the migration continues for over a decade. Transient internal sources of particulate matter, biogenic silica, organic matter, and carbonates, eventually average about 15-20% of sediments in the depositional basins of the lake. Over 50% of the bottom of the lake does not permanently accumulate sediments, and this pattern has remained consistent for thousands of years. At the present time these depositional basins contain vast quantities of excess nutrients and contaminants delivered over the past century.

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